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Abstract

Three space crane articulated-truss joint concepts are studied to evaluate their static structural performance over a range of geometric design parameters. Emphasis is placed on maintaining the four-longeron reference truss performance across the joint while allowing large-angle articulation. A maximum positive articulation angle and the actuator length ratio required to reach that angle are computed for each concept as the design parameters are varied. Configurations with a maximum articulation angle less than 120° or actuators requiring a length ratio over 2 are not considered. Tip rotation and lateral deflections of a truss beam with an articulated-truss joint at the midspan are used to select a point design (with fixed values of the design parameters) for each concept. Deflections for one point design are up to 40 percent higher than for the other two designs. Dynamic performance (natural frequencies, mode shapes, and maximum allowable velocity for an emergency stop scenario) of the three point designs is computed as a function of joint articulation angle. The two lowest frequencies of each point design are relatively insensitive to large variations in joint articulation angle. One point design has a higher maximum tip velocity for the emergency stop than the other designs.

Introduction

Proposed missions to the Moon and Mars are likely to require spacecraft too large to be launched into Earth orbit in an operational configuration. Consequently, these vehicles must be assembled from components launched separately. A major feature of a dedicated facility for on-orbit assembly of these vehicles is expected to be a large, dexterous manipulator, or space crane, for positioning and maneuvering large components (ref. 1). NASA's current capability for on-orbit payload handling is the Remote Manipulator System (RMS), a six-degree-of-freedom (DOF) arm that is used to deploy and retrieve payloads of up to 29 500 kg from the Space Shuttle orbiter cargo bay. The RMS features two high-stiffness graphite-epoxy booms (5 and 6 m in length and 0.34 m in diameter) that connect the six single-DOF joints and provide the majority of the 15.3-m reach capability of the arm. The RMS joints are geared mechanisms that allow large-angle rotation, but have low stiffness (ref. 2). Of the six RMS joints, four have symmetric ranges of motion from their stowed position, allowing both positive and negative rotation about the joint axis (ref. 3). The restricted reach envelope and reduced joint stiffness of the RMS limit its applicability for assembly of large and massive spacecraft. As an alternative to the RMS, a space crane is proposed that features stiffer articulated-truss joints and a larger reach envelope.

A space crane concept is shown in figure 1 attached to an in-space construction facility. Coarse positioning of the space crane tip is provided by three single-DOF articulated-truss joints between the three booms and one single-DOF rotary joint at the root. A multi-DOF manipulator at the tip is used for fine positioning of payloads. The three booms are lattice trusses, which offer both high stiffness and low mass. Large articulation angles may be achieved by proper selection of the articulated-truss joint geometry. Kinematic analyses presented in reference 4 show that a minimum range of motion from 0° to 120° at each joint is necessary for the space crane tip to reach all points in its work envelope. However, some additional range of motion in excess of 120° may be desirable for certain operations. The impact of this excess articulation range on space crane operations is beyond the scope of the present study. Several articulated-truss joint designs with two and four actuators were evaluated in reference 4. A joint design with two actuators in series was selected based on its kinematic performance (i.e., rigid-body positioning capability); maximizing the stiffness of this joint design was not a primary consideration.

In this study, three proposed concepts for a space crane articulated-truss joint are evaluated to determine their structural performance over a range of geometric design parameters. An objective of this study is to maintain a high percentage of the reference truss performance while allowing large-angle articulation with realistic actuator length ratios. To achieve this, the joint articulation range of motion and actuator length ratios are computed as functions of the geometric design parameters for each joint concept. Limits on the geometric design parameters that ensure adequate kinematic performance are established for the joint concepts. Next, the static structural performance of truss beams containing each joint concept is evaluated by computing tip rotations and lateral deflections with finite element methods. A point design (with fixed values of the geometric design parameters) is selected for each joint concept on the basis of structural performance relative to that of the reference truss. Finally, natural frequencies, mode shapes, and the maximum allowable tip velocity for an emergency stop scenario are computed as functions of the joint articulation angle for the three point designs.

Symbols

A	joint hinge axis nodes, joint concepts A, B, and C
B	hinged common node connecting actuators, joint concepts A, B, and C
C	hinged node connecting actuator to transition truss, joint concept A
D	trunnion node connecting actuator to transition truss, joint concept B
E	transition truss node, joint concept B
F	hinged node connecting actuator to transition truss, joint concept C
G	node limiting articulation range of motion, joint concept C
H	transition truss node, joint concept C
L_J	joint length, joint concept C
X_C	hinged node X-coordinate, joint concept A
X_D	trunnion node X-coordinate, joint concept B
Y_{BA}	central batten plane depth, joint concept A
Y_{BB}	central batten plane depth, joint concept B
Y_{BC}	central batten plane depth, joint concept C
Y_C	hinged node Y-coordinate, joint concept A
Y_D	trunnion node Y-coordinate, joint concept B

Joint Design Considerations

Truss Booms

A four-longeron truss is selected for the space crane because it has redundant members and is therefore more resistant to catastrophic failure. The reference truss geometry chosen for this study has a lacing pattern in which the face diagonals alternate directions through the truss depth and in adjacent bays. However, the batten plane diagonals are parallel, allowing clear lanes to attach utility trays to the interior of the truss bay. This truss configuration has a two-bay repeating unit (fig. 2(a)), where each bay is a cube with an edge length of 1 m. The aluminum truss members consist of a strut tube with an erectable joint at each end. The erectable joints are attached to fittings on the nodes. Erectable joint and strut tube stiffness properties are listed in table I (ref. 5). The torsional and bending stiffnesses of a truss beam (fig. 2(b)) built with this hardware are 2.75 MN-m^2/rad and 7.83 MN-m^2, respectively. A global coordinate system is oriented with the X-axis along the beam length, and the Y- and Z-axes in the plane of the battens.

Articulated-Truss Joints

Each of the three joint concepts evaluated in the present study uses a single pair of actuators in series to achieve large-angle joint articulation. Consequently, the truss bays that contain the actuators have only three longerons, and truss redundancy is sacrificed to avoid the problems associated with synchronizing two actuators in parallel. A transition truss structure is required to connect the four-longeron truss booms to the three-longeron articulated-truss joints. Three transition truss geometries will be evaluated here.

The variable-length actuators provide the forces necessary to effect rigid-body rotation of the truss booms. Since the actuators function as load-bearing structural elements in the articulated-truss joints, actuator end fittings may induce shear and bending loads that may cause the internal mechanism of the actuator to seize and fail. Thus, it is desirable to design the actuator end fittings so that only axial loads are transmitted to the actuators. It is also desirable to use actuators that, at any given length, exhibit linear axial load-displacement response, allowing improved predictability of joint behavior.

The actuator length ratio is defined as the distance between the ends of the actuator at a given articulation angle, divided by the distance between the ends of the actuator at an articulation angle of 0° where the two booms are collinear. Actuators that have a length ratio greater than 2 must extend to over twice their fully retracted length, which is undesirable because of the increased complexity and potential for nonlinear structural response. A length ratio of 2 represents a theoretical upper limit for an actuator with a single telescoping segment, since most actuators will have a length ratio less than 2 to accommodate the actuation mechanism and end fittings while still allowing the telescoping segments to overlap. A lower length ratio provides the structural designer with additional length for including any necessary hardware without reducing the joint articulation range.

The positive joint articulation angle is defined as the angle through which the joint rotates about

the joint hinge axis when the actuator is extended from its initial position at an articulation angle of 0°. The positive articulation limit is defined as the maximum angle through which the joint can be rotated without collision of the truss booms. Certain joint configurations are capable of rotating through a negative articulation angle, where the actuator is retracted from its initial position. This means that the actuator must be partially extended at an articulation angle of 0° in order to rotate through a negative articulation angle. The negative articulation limit is not examined in this study.

In the analysis models of these joint concepts, single-DOF hinges are used to connect the actuators to the transition truss structure and permit rigid-body articulation of the joints as the actuators are extended or retracted. These hinges should be located as close to the center of the truss nodes as possible to minimize load eccentricity through the joint. Although some separation of the hinge lines is necessary on the physical hardware, the two separate hinge elements are assumed to be collocated in the finite element models.

Articulated-Truss Joint Concepts

Common Features

Schematics of the three articulated-truss joint concepts are shown in figures 3(a), 4(a), and 5(a), and close-up perspective views are shown in figures 3(b), 4(b), and 5(b). Structural elements common to each of the three joint concepts are two variable-length actuators (represented by a heavy line weight in the schematics) and five single-DOF hinged nodes (shown with open circles). Positive or negative joint articulation is achieved by extending or retracting the actuators. Two of the three hinged nodes (nodes A) on the central batten plane form the joint hinge axis A-A, while the third node (node B) provides a common attachment point for one end of each actuator. The central batten plane A-B-A forms a plane of reflective symmetry for each joint concept. The remaining two hinged nodes (nodes C, D, and F in joint concepts A, B, and C, respectively) connect the actuator to the transition truss structure. The joint hinge axis A-A is parallel to the global Z-axis in each joint concept.

Joint Concepts

Joint concept A, shown in a schematic in figure 3(a) and in a perspective in figure 3(b), incorporates two three-longeron truss bays (with one of the longerons replaced by an actuator) between two bays of transition truss structure. The ends of each actuator are attached to the truss at nodes B and C, as shown in figure 3(a). Geometric design parameters identified for this joint concept are the perpendicular distance from the joint hinge axis A-A to the hinged common node B (Y_{BA}), and the X- and Y-coordinates of the hinged node C (X_C and Y_C). Discrete values of 0.75, 1.00, and 1.25 m are chosen for each of the three geometric design parameters, yielding 27 distinct configurations. All 27 configurations have a positive articulation limit of 180°, which occurs when the two truss booms are folded completely against each other.

Joint concept B, shown in a schematic in figure 4(a) and in a perspective in figure 4(b), utilizes the same transition truss geometry as joint concept A, but eliminates the three-longeron truss bays. Consequently, the actuators in this joint concept are not attached to the transition truss at both ends, but rather at one end (node B in fig. 4(a)) and at a point along the length of the actuator body (node D), referred to as a trunnion node. This actuator attachment scheme generates three physical constraints on the placement of the actuator in the transition truss. First, the actuator line of action B-D cannot intersect the joint hinge axis A-A, otherwise the actuator will not generate a moment about A-A. Second, B-D cannot pass through the interior of region A-A-D-E-E (node E connects the transition truss to the truss boom). Because the unsupported end of the actuator extends past node D, this constraint prevents the actuator from colliding with the truss boom as it pivots about node D during joint articulation. Also, access to the actuator for replacement or in-situ maintenance is severely restricted. Third, B-D cannot intersect the truss member between nodes E-E. If this constraint were not applied, the unsupported end of the actuator would intersect truss member E-E unless an actuator with a length ratio greater than 2 were used.

The three geometric design parameters identified for joint concept B are the perpendicular distance from the joint hinge axis A-A to the hinged common node B (Y_{BB}), and the X- and Y-coordinates of the trunnion node D (X_D and Y_D). Discrete values of 0.75, 1.00, and 1.25 m are selected for Y_{BB}; discrete values of 0.50, 0.75, and 1.00 m are chosen for X_D; and discrete values of 1.00 and 1.25 m are chosen for Y_D. All 18 configurations have a positive articulation limit of 180° as described previously for joint concept A. Physical constraints on the actuator line of action discussed previously are used to eliminate the nine joint configurations listed in table II from further consideration.

Joint concept C, shown in a schematic in figure 5(a) and in a perspective in figure 5(b),

incorporates truss booms that are rotated 45° about the X-axis with respect to the truss booms of joint concepts A and B. This results in a joint hinge axis A-A that is parallel to the internal diagonals of the truss booms. The two actuators are collinear with the longerons along the top of the truss booms, and the ends of the actuators are attached to the truss at nodes B and F, as shown in figure 5(a). The locations of the joint hinge axis in joint concepts A and B allow a full 180° of positive articulation from the 0° initial position. However, the positive articulation angle of joint concept C is limited by the collision of nodes G on the truss booms. This positive articulation limit depends on the location of the joint hinge axis and increases as the angle G-A-G increases.

The two geometric design parameters identified for joint concept C are the perpendicular distance from the joint hinge axis A-A to the hinged common node B (Y_{BC}), and the joint length L_J (the distance between nodes B and F). Discrete values chosen for Y_{BC} are 0.707, 0.966, and 1.225 m. The value of 0.707 m is chosen to make the central batten plane A-B-A an isosceles right triangle with equal-length legs of 1 m, and the 1.225-m value is chosen to make the central batten plane an equilateral triangle with 1.414-m legs. These two values of Y_{BC} may be achieved with standard reference truss hardware. The intermediate value of Y_{BC} is included for completeness. Four discrete values selected for L_J are 1.00, 1.50, 2.00, and 2.50 m, resulting in a total of 12 distinct analysis configurations for this joint concept.

Analysis Models

Reference Truss

A linear finite element model of a 14-bay reference truss beam is generated and shown in figure 6 (ref. 6). The 14-bay beam length is chosen because the beam behavior is found to be accurately predicted with Euler-Bernoulli beam theory. A cantilevered boundary condition is approximated by pinning the four nodes of the first batten plane to ground. Static loads of 125.81 N-m (X-axis torsion) and 177.93 N (Y- and Z-axis bending) are applied at the 15th batten plane at the free end of the truss beam. Each truss member is modeled as a single beam element with the effective axial stiffness computed from the data in table I by treating the truss member as three linear springs (i.e., two erectable joints and a strut tube) in series.

Articulated-Truss Joints

A finite element model of each joint concept is incorporated into a model of the reference truss beam. The two midspan bays (four bays for joint concept A) of truss are replaced by one of the three joint concepts described previously. The joints are rotated to an articulation angle of 0°, and the same static loads discussed previously are applied at the beam tip. The X-axis rotation and the Y- and Z-axis deflections at the tip of the truss beam containing the joint are computed and normalized by the corresponding displacements of an equal-length reference truss beam. Since varying L_J in joint concept C changes the total length of the truss beam from 14 to 17 m (in 1-m increments), reference truss models of the same corresponding length are used to compute tip rotations and deflections for these cases.

A representative articulated-truss joint finite element model is shown in figure 7. The two actuators are modeled as rigid beam elements since the purpose of this study is to isolate the effects of the joint geometry on structural performance. Single-DOF hinge elements, necessary for rigid-body articulation of the joint, are modeled as zero-length rigid elements with no rotational stiffness about the Z-axis. The eight hinge elements (two on each of the two nodes of the joint hinge axis, and one at each end of the actuators) are shown in figure 7 as dashed lines.

Selection of Point Designs

Selection of a point design (defined as having fixed values of the geometric design parameters) from each of the three joint concepts is discussed here along with the selection criteria used. Kinematic analyses are performed to determine the positive articulation limit and actuator length ratio as functions of the joint design parameters. Joint concepts that require an actuator with a length ratio greater than 2 to reach their positive articulation limit or do not have a positive articulation limit of at least 120° will not be considered as candidates for further analyses. The structural performance of the remaining articulated-truss joint concepts, based on the normalized torsional and bending deformations, is used to select a point design for each joint concept.

Joint Concept A

Because of its geometry, joint concept A has a positive articulation limit of 180°, and any combination of geometric design parameters meets the 120° minimum articulation angle requirement. The actuator length ratios required to reach 180° are shown in figure 8. The majority of the 27 configurations have length ratios greater than 2 and are eliminated. Actuator length ratios for the remaining nine configurations are between 1.71 and 1.97. These 9 configurations form a feasible domain of point designs for the static deflection analysis.

Static displacements for the nine feasible configurations of joint concept A are shown in figures 9–11 as functions of the geometric design parameters. The data are normalized by the tip rotation and lateral deflection of a 14-bay reference truss beam as discussed previously. The X-axis tip rotation, shown in figure 9, is independent of the batten plane depth Y_{BA}, but decreases as the hinge X- and Y-coordinates X_C and Y_C are increased. This insensitivity to Y_{BA} occurs because the torsional stiffness of the three-longeron truss bays depends only on the length of truss member A-C. Increases of at least 20 percent in the tip rotation result from the lower torsional stiffness of the three-longeron truss bays. The Y-axis tip deflection, shown in figure 10, is sensitive to variation of all the design parameters since this load case corresponds to bending about the joint hinge axis A-A. The lowest values of lateral deflection occur when both Y_C and Y_{BA} are greater than or equal to 1 m. The Z-axis tip deflection is shown in figure 11. These deflections are independent of Y_{BA} and nearly independent of X_C and Y_C, since the three design parameters are in the plane of the bending neutral axis and thus should not affect the Y-axis bending stiffness. The deflections are about 15 percent greater than for the reference truss because of the reduced bending stiffness of the three-longeron and transition truss bays.

The joint configurations where $Y_C = 1.25$ m have the lowest tip rotation, and joints where both Y_{BA} and $X_C = 0.75$ m have lower actuator length ratios than the other configurations. The configuration where both Y_{BA} and $X_C = 0.75$ m and $Y_C = 1.25$ m has a Y-axis tip deflection that is close to the reference truss tip deflection. Based on these considerations, the point design chosen for further analysis has both Y_{BA} and $X_C = 0.75$ m and $Y_C = 1.25$ m.

Joint Concept B

As noted previously, joint concept B has a positive articulation limit of 180°, and any combination of geometric design parameters meets the 120° minimum articulation angle. An actuator length ratio cannot be defined for joint concept B, since both actuator ends are not connected to the transition truss as in joints A and C.

The normalized static displacements for the nine acceptable configurations of joint concept B are shown in figures 12–14 as functions of the geometric design parameters. The X-axis tip rotation, shown in figure 12, is independent of the batten plane depth Y_{BB}, as noted for joint concept A. The tip rotation has a maximum variation of only 7 percent over the range of parameters studied, with the lowest value occurring when $X_D = 1.00$ m and $Y_D = 1.25$ m. The Y-axis tip deflection for joint concept B, shown in figure 13, is more sensitive to variation of the design parameters than the corresponding tip deflection for joint concept A. A lateral deflection of almost 3.5 times the reference truss value is predicted for the joint configuration where both X_D and $Y_{BB} = 0.75$ m and $Y_D = 1.25$ m. In this configuration the actuator line of action B-D is nearly parallel to the Y-axis, resulting in a very low bending stiffness about the global Z-axis. The lowest deflections occur for all values of X_D when both Y_D and $Y_{BB} = 1.25$ m. The Z-axis tip deflection, shown in figure 14, is nearly constant over the range of parameters studied, with a 5-percent reduction observed as X_D is increased.

Larger values of both Y_{BB} and Y_D yield higher torsional stiffnesses. In addition, larger values of X_D increase the bending stiffnesses of the joint. Based on these observations, the design parameters selected are $Y_{BB} = 1.25$ m, $X_D = 1.00$ m, and $Y_D = 1.25$ m. Negative articulation angles are not possible for this point design because the central batten plane A-B-A and transition truss batten planes A-D-A are coplanar. Some physical separation of these nodes would be necessary if this design were fabricated.

Joint Concept C

The positive articulation limits for joint concept C are computed as functions of the geometric design parameters chosen. The positive articulation limit, shown in figure 15, increases as the joint length L_J and batten plane depth Y_{BC} are increased. The joint configuration where $L_J = 1.00$ m and $Y_{BC} = 0.707$ m has a positive articulation limit of 110°. This joint is not a viable candidate for further analyses since it does not meet the minimum articulation requirement of 120°. The actuator length ratios for the remaining joint configurations are shown in figure 16. The computed ratios are almost all less than 2. The configuration where $L_J = 1.00$ m and $Y_{BC} = 1.225$ m is eliminated from further consideration because the length ratio is greater than 2.

Normalized static displacements for joint concept C are shown in figures 17–19 as functions of the geometric design parameters. The tip rotation and lateral deflection of a 14- to 17-bay truss beam are used to normalize the joint beam deformations, since the joint beam length varies as L_J increases. The X-axis tip rotation, shown in figure 17, increases with increasing L_J and Y_{BC}. The maximum tip rotation is over 1.5 times the rotation of an equal-length reference truss beam and occurs because the torsional stiffness of the joint decreases as L_J is increased. The Y-axis tip deflection, shown in figure 18, decreases as

both L_J and Y_{BC} are increased. The Z-axis bending stiffness depends on the truss depth and thus increases as Y_{BC} is increased. The Z-axis tip deflection is roughly constant as L_J is varied and increases as Y_{BC} is increased, as shown in figure 19. This occurs because the angle between truss member A-H and the row of longerons that provide the Y-axis bending stiffness is increased as Y_{BC} is increased.

Since the joint configurations where $L_J = 2.00$ and 2.50 m have large tip rotations, the joint length should be less than or equal to 1.50 m. The articulation limits for $L_J = 1.00$ m are too restrictive, so the joint length is chosen to be 1.50 m. The lateral tip deflections most closely match the reference truss performance when $Y_{BC} = 0.707$ m. Based on these considerations, the point design selected has $L_J = 1.50$ m and $Y_{BC} = 0.707$ m. The positive articulation limit of this design is 130°. The performance of the three selected point designs is given in table III, and the point designs are shown in figure 20. The positive articulation limit and actuator length ratio required to reach the positive articulation limit are listed with the normalized tip displacements for each point design. Joints A and B have higher positive articulation limits than joint C. Because joint C has a lower positive articulation limit, its actuator has a lower length ratio than the actuator in joint A. Joints B and C have static tip displacements that are very close to the reference truss values.

Dynamic Analysis of Point Designs

The structural dynamic performance of the three point designs is presented and discussed here. The finite element models used in the static analyses are modified to allow the outboard boom to be rotated to a specified angle. The finite element models of joint concepts A and B are 14 bays (14 m) in length. One truss bay is removed from the beam root of joint concept C to make its overall length 14 m. *Since the joint hinge axis of joint concept C is not the same distance from the cantilever as the axes of joints A and B, the joints cannot be compared directly.* Measured and estimated reference truss and prototype articulated-truss joint hardware masses are shown in table IV. Normal mode vibration analyses are performed for the three point designs as the joint articulation angle is varied from 0° to 120° in 5° increments. Frequencies are computed both with and without a 453.59-kg tip mass. The transient response of each point design with a tip mass to the emergency stop scenario developed in reference 4 is computed and discussed.

The lowest four natural frequencies for joints A, B, and C without a tip mass are plotted as functions of the joint articulation angle in figures 21–23. Mode shapes are listed for the 0° and 120° articulation angles. The mode shapes for the 0° case are similar to those of a cantilevered beam. These modes change to beam root bending and torsional modes as the joint is rotated to 120°. The lowest two frequencies remain in the vicinity of 2 Hz over the entire articulation range, while the third and fourth frequencies drop from over 10 Hz at 0° to between 4 and 7 Hz at 120°. The minimum frequency for each point design and the articulation angle at which it occurs are 1.85 Hz at 85° for joint A, 2.02 Hz at 75° for joint B, and 2.03 Hz at 120° for joint C. The lowest four natural frequencies for joints A, B, and C with a 453.59-kg tip mass are plotted in figures 24–26. This tip mass, representative of payloads that might be manipulated on orbit, is equally distributed at the four nodes at the beam tip. The mode shapes are almost identical to the mode shapes without the tip mass. Three of the four frequencies show an invariance to changes in the joint articulation angle.

The emergency stop scenario developed in reference 4 is used to compute a maximum allowable tip velocity based on buckling of the truss members. The Euler bucking load is used because it is a conservative estimate of member buckling, a primary failure mode in lattice trusses. The allowable compressive load of a truss member is determined by dividing its Euler buckling load by a factor of safety of 1.40. A 453.59-kg tip mass is located at the beam tip, and modal damping of 0.50 percent is assumed for these analyses. The articulation range and increment are identical to those used in the normal modes analysis. The first 10 normal modes are computed at each articulation angle, and a constant $1g$ inertial load is applied (for 1 s) in the global X-, Y-, and Z-directions. The transient response of the structure in the same direction as the load is computed. The magnitude and location of the maximum truss member load is identified for each transient response case, and the allowable compressive load for the critically loaded member is divided by the computed maximum load. This ratio is multiplied by the magnitude of the inertial load and integrated over the 1-s pulse duration to obtain the maximum allowable tip velocity in each direction.

The maximum allowable tip velocities computed for the three point designs are shown in figures 27–29. The Z-axis inertial loads are the limiting value in almost every case. The location of the critically loaded truss member is different for each point design, joint articulation angle, and load direction. The maximum allowable tip velocities in each direction are shown in table V for joints A, B, and C with the articulation angle at which they occur. The lower tip

velocities computed for joints A and C result from the lower buckling load of the long truss members in the articulated-truss joint. The allowable tip velocity of the point designs may be increased by increasing the Euler buckling load of the critically loaded members. The mode shapes associated with the lowest allowable tip velocities are beam root torsion for joints A and B, and Z-axis bending for joint C. These mode shapes and the critically loaded truss members for that joint articulation angle are shown in figures 30–32.

Concluding Remarks

Three articulated-truss joint concepts for the space crane are described and parametrically evaluated to determine their static structural performance. For each joint concept, a point design is selected with a minimum positive articulation limit of 120°, an actuator length ratio less than 2.00, and minimum tip displacements. Computed displacements for joint A are up to 40 percent higher than the corresponding reference truss values. The displacements for joints B and C are all within 10 percent of the reference truss values. The three point designs are analyzed to determine their structural dynamic performance (natural frequencies, mode shapes, and transient response) as a function of the joint articulation angle. The lowest two natural frequencies are relatively insensitive to large variations in the joint articulation angle for all three point designs with and without a tip mass. The maximum allowable tip velocity (based on Euler buckling of the truss members) predicted from an emergency stop scenario with a tip mass is highest for joint B. The tip velocities for joints A and C are limited by loads in the long truss members in the articulated-truss joint.

Based on the results of these analyses, it appears that although substantial differences in static performance exist between the three point designs, the differences in the dynamic performance of the joints are less significant. Since dynamic performance is likely to be a significant consideration in choosing an articulating joint, any of the three point designs selected should be capable of performing the tasks required in a space crane. Consequently, criteria other than structural performance may be used to select a final design.

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Abstract

Three space crane articulated-truss joint concepts are studied to evaluate their static structural performance over a range of geometric design parameters. Emphasis is placed on maintaining the four-longeron reference truss performance across the joint while allowing large-angle articulation. A maximum positive articulation angle and the actuator length ratio required to reach that angle are computed for each concept as the design parameters are varied. Configurations with a maximum articulation angle less than 120° or actuators requiring a length ratio over 2 are not considered. Tip rotation and lateral deflections of a truss beam with an articulated-truss joint at the midspan are used to select a point design (with fixed values of the design parameters) for each concept. Deflections for one point design are up to 40 percent higher than for the other two designs. Dynamic performance (natural frequencies, mode shapes, and maximum allowable velocity for an emergency stop scenario) of the three point designs is computed as a function of joint articulation angle. The two lowest frequencies of each point design are relatively insensitive to large variations in joint articulation angle. One point design has a higher maximum tip velocity for the emergency stop than the other designs.

Introduction

Proposed missions to the Moon and Mars are likely to require spacecraft too large to be launched into Earth orbit in an operational configuration. Consequently, these vehicles must be assembled from components launched separately. A major feature of a dedicated facility for on-orbit assembly of these vehicles is expected to be a large, dexterous manipulator, or space crane, for positioning and maneuvering large components (ref. 1). NASA's current capability for on-orbit payload handling is the Remote Manipulator System (RMS), a six-degree-of-freedom (DOF) arm that is used to deploy and retrieve payloads of up to 29 500 kg from the Space Shuttle orbiter cargo bay. The RMS features two high-stiffness graphite-epoxy booms (5 and 6 m in length and 0.34 m in diameter) that connect the six single-DOF joints and provide the majority of the 15.3-m reach capability of the arm. The RMS joints are geared mechanisms that allow large-angle rotation, but have low stiffness (ref. 2). Of the six RMS joints, four have symmetric ranges of motion from their stowed position, allowing both positive and negative rotation about the joint axis (ref. 3). The restricted reach envelope and reduced joint stiffness of the RMS limit its applicability for assembly of large and massive spacecraft. As an alternative to the RMS, a space crane is proposed that features stiffer articulated-truss joints and a larger reach envelope.

A space crane concept is shown in figure 1 attached to an in-space construction facility. Coarse positioning of the space crane tip is provided by three single-DOF articulated-truss joints between the three booms and one single-DOF rotary joint at the root. A multi-DOF manipulator at the tip is used for fine positioning of payloads. The three booms are lattice trusses, which offer both high stiffness and low mass. Large articulation angles may be achieved by proper selection of the articulated-truss joint geometry. Kinematic analyses presented in reference 4 show that a minimum range of motion from 0° to 120° at each joint is necessary for the space crane tip to reach all points in its work envelope. However, some additional range of motion in excess of 120° may be desirable for certain operations. The impact of this excess articulation range on space crane operations is beyond the scope of the present study. Several articulated-truss joint designs with two and four actuators were evaluated in reference 4. A joint design with two actuators in series was selected based on its kinematic performance (i.e., rigid-body positioning capability); maximizing the stiffness of this joint design was not a primary consideration.

In this study, three proposed concepts for a space crane articulated-truss joint are evaluated to determine their structural performance over a range of geometric design parameters. An objective of this study is to maintain a high percentage of the reference truss performance while allowing large-angle articulation with realistic actuator length ratios. To achieve this, the joint articulation range of motion and actuator length ratios are computed as functions of the geometric design parameters for each joint concept. Limits on the geometric design parameters that ensure adequate kinematic performance are established for the joint concepts. Next, the static structural performance of truss beams containing each joint concept is evaluated by computing tip rotations and lateral deflections with finite element methods. A point design (with fixed values of the geometric design parameters) is selected for each joint concept on the basis of structural performance relative to that of the reference truss. Finally, natural frequencies, mode shapes, and the maximum allowable tip velocity for an emergency stop scenario are computed as functions of the joint articulation angle for the three point designs.

Symbols

A — joint hinge axis nodes, joint concepts A, B, and C

B — hinged common node connecting actuators, joint concepts A, B, and C

C — hinged node connecting actuator to transition truss, joint concept A

D — trunnion node connecting actuator to transition truss, joint concept B

E — transition truss node, joint concept B

F — hinged node connecting actuator to transition truss, joint concept C

G — node limiting articulation range of motion, joint concept C

H — transition truss node, joint concept C

L_J — joint length, joint concept C

X_C — hinged node X-coordinate, joint concept A

X_D — trunnion node X-coordinate, joint concept B

Y_{BA} — central batten plane depth, joint concept A

Y_{BB} — central batten plane depth, joint concept B

Y_{BC} — central batten plane depth, joint concept C

Y_C — hinged node Y-coordinate, joint concept A

Y_D — trunnion node Y-coordinate, joint concept B

Joint Design Considerations

Truss Booms

A four-longeron truss is selected for the space crane because it has redundant members and is therefore more resistant to catastrophic failure. The reference truss geometry chosen for this study has a lacing pattern in which the face diagonals alternate directions through the truss depth and in adjacent bays. However, the batten plane diagonals are parallel, allowing clear lanes to attach utility trays to the interior of the truss bay. This truss configuration has a two-bay repeating unit (fig. 2(a)), where each bay is a cube with an edge length of 1 m. The aluminum truss members consist of a strut tube with an erectable joint at each end. The erectable joints are attached to fittings on the nodes. Erectable joint and strut tube stiffness properties are listed in table I (ref. 5). The torsional and bending stiffnesses of a truss beam (fig. 2(b)) built with this hardware are 2.75 MN-m^2/rad and 7.83 MN-m^2, respectively. A global coordinate system is oriented with the X-axis along the beam length, and the Y- and Z-axes in the plane of the battens.

Articulated-Truss Joints

Each of the three joint concepts evaluated in the present study uses a single pair of actuators in series to achieve large-angle joint articulation. Consequently, the truss bays that contain the actuators have only three longerons, and truss redundancy is sacrificed to avoid the problems associated with synchronizing two actuators in parallel. A transition truss structure is required to connect the four-longeron truss booms to the three-longeron articulated-truss joints. Three transition truss geometries will be evaluated here.

The variable-length actuators provide the forces necessary to effect rigid-body rotation of the truss booms. Since the actuators function as load-bearing structural elements in the articulated-truss joints, actuator end fittings may induce shear and bending loads that may cause the internal mechanism of the actuator to seize and fail. Thus, it is desirable to design the actuator end fittings so that only axial loads are transmitted to the actuators. It is also desirable to use actuators that, at any given length, exhibit linear axial load-displacement response, allowing improved predictability of joint behavior.

The actuator length ratio is defined as the distance between the ends of the actuator at a given articulation angle, divided by the distance between the ends of the actuator at an articulation angle of 0° where the two booms are collinear. Actuators that have a length ratio greater than 2 must extend to over twice their fully retracted length, which is undesirable because of the increased complexity and potential for nonlinear structural response. A length ratio of 2 represents a theoretical upper limit for an actuator with a single telescoping segment, since most actuators will have a length ratio less than 2 to accommodate the actuation mechanism and end fittings while still allowing the telescoping segments to overlap. A lower length ratio provides the structural designer with additional length for including any necessary hardware without reducing the joint articulation range.

The positive joint articulation angle is defined as the angle through which the joint rotates about the joint hinge axis when the actuator is extended from its ini-

tial position at an articulation angle of 0°. The positive articulation limit is defined as the maximum angle through which the joint can be rotated without collision of the truss booms. Certain joint configurations are capable of rotating through a negative articulation angle, where the actuator is retracted from its initial position. This means that the actuator must be partially extended at an articulation angle of 0° in order to rotate through a negative articulation angle. The negative articulation limit is not examined in this study.

In the analysis models of these joint concepts, single-DOF hinges are used to connect the actuators to the transition truss structure and permit rigid-body articulation of the joints as the actuators are extended or retracted. These hinges should be located as close to the center of the truss nodes as possible to minimize load eccentricity through the joint. Although some separation of the hinge lines is necessary on the physical hardware, the two separate hinge elements are assumed to be collocated in the finite element models.

Articulated-Truss Joint Concepts

Common Features

Schematics of the three articulated-truss joint concepts are shown in figures 3(a), 4(a), and 5(a), and close-up perspective views are shown in figures 3(b), 4(b), and 5(b). Structural elements common to each of the three joint concepts are two variable-length actuators (represented by a heavy line weight in the schematics) and five single-DOF hinged nodes (shown with open circles). Positive or negative joint articulation is achieved by extending or retracting the actuators. Two of the three hinged nodes (nodes A) on the central batten plane form the joint hinge axis A-A, while the third node (node B) provides a common attachment point for one end of each actuator. The central batten plane A-B-A forms a plane of reflective symmetry for each joint concept. The remaining two hinged nodes (nodes C, D, and F in joint concepts A, B, and C, respectively) connect the actuator to the transition truss structure. The joint hinge axis A-A is parallel to the global Z-axis in each joint concept.

Joint Concepts

Joint concept A, shown in a schematic in figure 3(a) and in a perspective in figure 3(b), incorporates two three-longeron truss bays (with one of the longerons replaced by an actuator) between two bays of transition truss structure. The ends of each actuator are attached to the truss at nodes B and C, as shown in figure 3(a). Geometric design parameters identified for this joint concept are the perpendicular distance from the joint hinge axis A-A to the hinged common node B (Y_{BA}), and the X- and Y-coordinates of the hinged node C (X_C and Y_C). Discrete values of 0.75, 1.00, and 1.25 m are chosen for each of the three geometric design parameters, yielding 27 distinct configurations. All 27 configurations have a positive articulation limit of 180°, which occurs when the two truss booms are folded completely against each other.

Joint concept B, shown in a schematic in figure 4(a) and in a perspective in figure 4(b), utilizes the same transition truss geometry as joint concept A, but eliminates the three-longeron truss bays. Consequently, the actuators in this joint concept are not attached to the transition truss at both ends, but rather at one end (node B in fig. 4(a)) and at a point along the length of the actuator body (node D), referred to as a trunnion node. This actuator attachment scheme generates three physical constraints on the placement of the actuator in the transition truss. First, the actuator line of action B-D cannot intersect the joint hinge axis A-A, otherwise the actuator will not generate a moment about A-A. Second, B-D cannot pass through the interior of region A-A-D-E-E (node E connects the transition truss to the truss boom). Because the unsupported end of the actuator extends past node D, this constraint prevents the actuator from colliding with the truss boom as it pivots about node D during joint articulation. Also, access to the actuator for replacement or in-situ maintenance is severely restricted. Third, B-D cannot intersect the truss member between nodes E-E. If this constraint were not applied, the unsupported end of the actuator would intersect truss member E-E unless an actuator with a length ratio greater than 2 were used.

The three geometric design parameters identified for joint concept B are the perpendicular distance from the joint hinge axis A-A to the hinged common node B (Y_{BB}), and the X- and Y-coordinates of the trunnion node D (X_D and Y_D). Discrete values of 0.75, 1.00, and 1.25 m are selected for Y_{BB}; discrete values of 0.50, 0.75, and 1.00 m are chosen for X_D; and discrete values of 1.00 and 1.25 m are chosen for Y_D. All 18 configurations have a positive articulation limit of 180° as described previously for joint concept A. Physical constraints on the actuator line of action discussed previously are used to eliminate the nine joint configurations listed in table II from further consideration.

Joint concept C, shown in a schematic in figure 5(a) and in a perspective in figure 5(b), incorporates truss booms that are rotated 45° about the X-axis with respect to the truss booms of joint concepts A and B. This results in a joint hinge axis A-A that is parallel to the internal diagonals of the truss booms. The two actuators are collinear with the longerons along the top of the truss booms, and the ends of the actuators are attached to the truss at nodes B and F, as shown in figure 5(a). The locations of the

joint hinge axis in joint concepts A and B allow a full 180° of positive articulation from the 0° initial position. However, the positive articulation angle of joint concept C is limited by the collision of nodes G on the truss booms. This positive articulation limit depends on the location of the joint hinge axis and increases as the angle G-A-G increases.

The two geometric design parameters identified for joint concept C are the perpendicular distance from the joint hinge axis A-A to the hinged common node B (Y_{BC}), and the joint length L_J (the distance between nodes B and F). Discrete values chosen for Y_{BC} are 0.707, 0.966, and 1.225 m. The value of 0.707 m is chosen to make the central batten plane A-B-A an isosceles right triangle with equal-length legs of 1 m, and the 1.225-m value is chosen to make the central batten plane an equilateral triangle with 1.414-m legs. These two values of Y_{BC} may be achieved with standard reference truss hardware. The intermediate value of Y_{BC} is included for completeness. Four discrete values selected for L_J are 1.00, 1.50, 2.00, and 2.50 m, resulting in a total of 12 distinct analysis configurations for this joint concept.

Analysis Models

Reference Truss

A linear finite element model of a 14-bay reference truss beam is generated and shown in figure 6 (ref. 6). The 14-bay beam length is chosen because the beam behavior is found to be accurately predicted with Euler-Bernoulli beam theory. A cantilevered boundary condition is approximated by pinning the four nodes of the first batten plane to ground. Static loads of 125.81 N-m (X-axis torsion) and 177.93 N (Y- and Z-axis bending) are applied at the 15th batten plane at the free end of the truss beam. Each truss member is modeled as a single beam element with the effective axial stiffness computed from the data in table I by treating the truss member as three linear springs (i.e., two erectable joints and a strut tube) in series.

Articulated-Truss Joints

A finite element model of each joint concept is incorporated into a model of the reference truss beam. The two midspan bays (four bays for joint concept A) of truss are replaced by one of the three joint concepts described previously. The joints are rotated to an articulation angle of 0°, and the same static loads discussed previously are applied at the beam tip. The X-axis rotation and the Y- and Z-axis deflections at the tip of the truss beam containing the joint are computed and normalized by the corresponding displacements of an equal-length reference truss beam. Since varying L_J in joint concept C changes the total length of the truss beam from 14 to 17 m (in 1-m increments), reference truss models of the same corresponding length are used to compute tip rotations and deflections for these cases.

A representative articulated-truss joint finite element model is shown in figure 7. The two actuators are modeled as rigid beam elements since the purpose of this study is to isolate the effects of the joint geometry on structural performance. Single-DOF hinge elements, necessary for rigid-body articulation of the joint, are modeled as zero-length rigid elements with no rotational stiffness about the Z-axis. The eight hinge elements (two on each of the two nodes of the joint hinge axis, and one at each end of the actuators) are shown in figure 7 as dashed lines.

Selection of Point Designs

Selection of a point design (defined as having fixed values of the geometric design parameters) from each of the three joint concepts is discussed here along with the selection criteria used. Kinematic analyses are performed to determine the positive articulation limit and actuator length ratio as functions of the joint design parameters. Joint concepts that require an actuator with a length ratio greater than 2 to reach their positive articulation limit or do not have a positive articulation limit of at least 120° will not be considered as candidates for further analyses. The structural performance of the remaining articulated-truss joint concepts, based on the normalized torsional and bending deformations, is used to select a point design for each joint concept.

Joint Concept A

Because of its geometry, joint concept A has a positive articulation limit of 180°, and any combination of geometric design parameters meets the 120° minimum articulation angle requirement. The actuator length ratios required to reach 180° are shown in figure 8. The majority of the 27 configurations have length ratios greater than 2 and are eliminated. Actuator length ratios for the remaining nine configurations are between 1.71 and 1.97. These 9 configurations form a feasible domain of point designs for the static deflection analysis.

Static displacements for the nine feasible configurations of joint concept A are shown in figures 9–11 as functions of the geometric design parameters. The data are normalized by the tip rotation and lateral deflection of a 14-bay reference truss beam as discussed previously. The X-axis tip rotation, shown in figure 9, is independent of the batten plane depth Y_{BA}, but decreases as the hinge X- and Y-coordinates X_C and Y_C are increased. This insensitivity to Y_{BA} occurs because the torsional stiffness of the three-longeron truss bays

depends only on the length of truss member A-C. Increases of at least 20 percent in the tip rotation result from the lower torsional stiffness of the three-longeron truss bays. The Y-axis tip deflection, shown in figure 10, is sensitive to variation of all the design parameters since this load case corresponds to bending about the joint hinge axis A-A. The lowest values of lateral deflection occur when both Y_C and Y_{BA} are greater than or equal to 1 m. The Z-axis tip deflection is shown in figure 11. These deflections are independent of Y_{BA} and nearly independent of X_C and Y_C, since the three design parameters are in the plane of the bending neutral axis and thus should not affect the Y-axis bending stiffness. The deflections are about 15 percent greater than for the reference truss because of the reduced bending stiffness of the three-longeron and transition truss bays.

The joint configurations where $Y_C = 1.25$ m have the lowest tip rotation, and joints where both Y_{BA} and $X_C = 0.75$ m have lower actuator length ratios than the other configurations. The configuration where both Y_{BA} and $X_C = 0.75$ m and $Y_C = 1.25$ m has a Y-axis tip deflection that is close to the reference truss tip deflection. Based on these considerations, the point design chosen for further analysis has both Y_{BA} and $X_C = 0.75$ m and $Y_C = 1.25$ m.

Joint Concept B

As noted previously, joint concept B has a positive articulation limit of 180°, and any combination of geometric design parameters meets the 120° minimum articulation angle. An actuator length ratio cannot be defined for joint concept B, since both actuator ends are not connected to the transition truss as in joints A and C.

The normalized static displacements for the nine acceptable configurations of joint concept B are shown in figures 12–14 as functions of the geometric design parameters. The X-axis tip rotation, shown in figure 12, is independent of the batten plane depth Y_{BB}, as noted for joint concept A. The tip rotation has a maximum variation of only 7 percent over the range of parameters studied, with the lowest value occurring when $X_D = 1.00$ m and $Y_D = 1.25$ m. The Y-axis tip deflection for joint concept B, shown in figure 13, is more sensitive to variation of the design parameters than the corresponding tip deflection for joint concept A. A lateral deflection of almost 3.5 times the reference truss value is predicted for the joint configuration where both X_D and $Y_{BB} = 0.75$ m and $Y_D = 1.25$ m. In this configuration the actuator line of action B-D is nearly parallel to the Y-axis, resulting in a very low bending stiffness about the global Z-axis. The lowest deflections occur for all values of X_D when both Y_D and $Y_{BB} = 1.25$ m. The Z-axis tip deflection, shown in figure 14, is nearly constant over the range of parameters studied, with a 5-percent reduction observed as X_D is increased.

Larger values of both Y_{BB} and Y_D yield higher torsional stiffnesses. In addition, larger values of X_D increase the bending stiffnesses of the joint. Based on these observations, the design parameters selected are $Y_{BB} = 1.25$ m, $X_D = 1.00$ m, and $Y_D = 1.25$ m. Negative articulation angles are not possible for this point design because the central batten plane A-B-A and transition truss batten planes A-D-A are coplanar. Some physical separation of these nodes would be necessary if this design were fabricated.

Joint Concept C

The positive articulation limits for joint concept C are computed as functions of the geometric design parameters chosen. The positive articulation limit, shown in figure 15, increases as the joint length L_J and batten plane depth Y_{BC} are increased. The joint configuration where $L_J = 1.00$ m and $Y_{BC} = 0.707$ m has a positive articulation limit of 110°. This joint is not a viable candidate for further analyses since it does not meet the minimum articulation requirement of 120°. The actuator length ratios for the remaining joint configurations are shown in figure 16. The computed ratios are almost all less than 2. The configuration where $L_J = 1.00$ m and $Y_{BC} = 1.225$ m is eliminated from further consideration because the length ratio is greater than 2.

Normalized static displacements for joint concept C are shown in figures 17–19 as functions of the geometric design parameters. The tip rotation and lateral deflection of a 14- to 17-bay truss beam are used to normalize the joint beam deformations, since the joint beam length varies as L_J increases. The X-axis tip rotation, shown in figure 17, increases with increasing L_J and Y_{BC}. The maximum tip rotation is over 1.5 times the rotation of an equal-length reference truss beam and occurs because the torsional stiffness of the joint decreases as L_J is increased. The Y-axis tip deflection, shown in figure 18, decreases as both L_J and Y_{BC} are increased. The Z-axis bending stiffness depends on the truss depth and thus increases as Y_{BC} is increased. The Z-axis tip deflection is roughly constant as L_J is varied and increases as Y_{BC} is increased, as shown in figure 19. This occurs because the angle between truss member A-H and the row of longerons that provide the Y-axis bending stiffness is increased as Y_{BC} is increased.

Since the joint configurations where $L_J = 2.00$ and 2.50 m have large tip rotations, the joint length should be less than or equal to 1.50 m. The articulation limits for $L_J = 1.00$ m are too restrictive, so the joint length is chosen to be 1.50 m. The lateral tip deflections most closely match the reference truss performance when $Y_{BC} = 0.707$ m. Based on these considerations, the

point design selected has $L_J = 1.50$ m and $Y_{BC} = 0.707$ m. The positive articulation limit of this design is 130°. The performance of the three selected point designs is given in table III, and the point designs are shown in figure 20. The positive articulation limit and actuator length ratio required to reach the positive articulation limit are listed with the normalized tip displacements for each point design. Joints A and B have higher positive articulation limits than joint C. Because joint C has a lower positive articulation limit, its actuator has a lower length ratio than the actuator in joint A. Joints B and C have static tip displacements that are very close to the reference truss values.

Dynamic Analysis of Point Designs

The structural dynamic performance of the three point designs is presented and discussed here. The finite element models used in the static analyses are modified to allow the outboard boom to be rotated to a specified angle. The finite element models of joint concepts A and B are 14 bays (14 m) in length. One truss bay is removed from the beam root of joint concept C to make its overall length 14 m. *Since the joint hinge axis of joint concept C is not the same distance from the cantilever as the axes of joints A and B, the joints cannot be compared directly.* Measured and estimated reference truss and prototype articulated-truss joint hardware masses are shown in table IV. Normal mode vibration analyses are performed for the three point designs as the joint articulation angle is varied from 0° to 120° in 5° increments. Frequencies are computed both with and without a 453.59-kg tip mass. The transient response of each point design with a tip mass to the emergency stop scenario developed in reference 4 is computed and discussed.

The lowest four natural frequencies for joints A, B, and C without a tip mass are plotted as functions of the joint articulation angle in figures 21–23. Mode shapes are listed for the 0° and 120° articulation angles. The mode shapes for the 0° case are similar to those of a cantilevered beam. These modes change to beam root bending and torsional modes as the joint is rotated to 120°. The lowest two frequencies remain in the vicinity of 2 Hz over the entire articulation range, while the third and fourth frequencies drop from over 10 Hz at 0° to between 4 and 7 Hz at 120°. The minimum frequency for each point design and the articulation angle at which it occurs are 1.85 Hz at 85° for joint A, 2.02 Hz at 75° for joint B, and 2.03 Hz at 120° for joint C. The lowest four natural frequencies for joints A, B, and C with a 453.59-kg tip mass are plotted in figures 24–26. This tip mass, representative of payloads that might be manipulated on orbit, is equally distributed at the four nodes at the beam tip. The mode shapes are almost identical to the mode shapes without the tip mass. Three of the four frequencies show an invariance to changes in the joint articulation angle.

The emergency stop scenario developed in reference 4 is used to compute a maximum allowable tip velocity based on buckling of the truss members. The Euler bucking load is used because it is a conservative estimate of member buckling, a primary failure mode in lattice trusses. The allowable compressive load of a truss member is determined by dividing its Euler buckling load by a factor of safety of 1.40. A 453.59-kg tip mass is located at the beam tip, and modal damping of 0.50 percent is assumed for these analyses. The articulation range and increment are identical to those used in the normal modes analysis. The first 10 normal modes are computed at each articulation angle, and a constant $1g$ inertial load is applied (for 1 s) in the global X-, Y-, and Z-directions. The transient response of the structure in the same direction as the load is computed. The magnitude and location of the maximum truss member load is identified for each transient response case, and the allowable compressive load for the critically loaded member is divided by the computed maximum load. This ratio is multiplied by the magnitude of the inertial load and integrated over the 1-s pulse duration to obtain the maximum allowable tip velocity in each direction.

The maximum allowable tip velocities computed for the three point designs are shown in figures 27–29. The Z-axis inertial loads are the limiting value in almost every case. The location of the critically loaded truss member is different for each point design, joint articulation angle, and load direction. The maximum allowable tip velocities in each direction are shown in table V for joints A, B, and C with the articulation angle at which they occur. The lower tip velocities computed for joints A and C result from the lower buckling load of the long truss members in the articulated-truss joint. The allowable tip velocity of the point designs may be increased by increasing the Euler buckling load of the critically loaded members. The mode shapes associated with the lowest allowable tip velocities are beam root torsion for joints A and B, and Z-axis bending for joint C. These mode shapes and the critically loaded truss members for that joint articulation angle are shown in figures 30–32.

Concluding Remarks

Three articulated-truss joint concepts for the space crane are described and parametrically evaluated to determine their static structural performance. For each joint concept, a point design is selected with a minimum positive articulation limit of 120°, an actuator length ratio less than 2.00, and minimum tip displacements.

Computed displacements for joint A are up to 40 percent higher than the corresponding reference truss values. The displacements for joints B and C are all within 10 percent of the reference truss values. The three point designs are analyzed to determine their structural dynamic performance (natural frequencies, mode shapes, and transient response) as a function of the joint articulation angle. The lowest two natural frequencies are relatively insensitive to large variations in the joint articulation angle for all three point designs with and without a tip mass. The maximum allowable tip velocity (based on Euler buckling of the truss members) predicted from an emergency stop scenario with a tip mass is highest for joint B. The tip velocities for joints A and C are limited by loads in the long truss members in the articulated-truss joint.

Based on the results of these analyses, it appears that although substantial differences in static performance exist between the three point designs, the differences in the dynamic performance of the joints are less significant. Since dynamic performance is likely to be a significant consideration in choosing an articulating joint, any of the three point designs selected should be capable of performing the tasks required in a space crane. Consequently, criteria other than structural performance may be used to select a final design.

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Table I. Truss Hardware Stiffness Properties

Truss member lengths (between node centers):	
Battens/longerons, m	1
Diagonals, m	1.414
Measured erectable joint properties:	
Length (node center to strut tube end), m	0.13
Axial stiffness, MN	8.45
Average bending stiffness, N-m^2	403.21
Estimated strut tube properties:	
Batten/longeron length (between strut tube ends), m	0.74
Diagonal length (between strut tube ends), m	1.15
Cross-sectional area, m^2	1.11×10^{-4}
Cross-sectional moment of inertia, m^4	7.96×10^{-9}
Axial stiffness, MN	7.63
Bending stiffness, N-m^2	548.48

Table II. Joint Concept B Configurations Eliminated by Actuator Line-of-Action Constraints

Y_{BB}, m	X_D, m	Y_D, m	Reason eliminated
0.75	1.00	1.00	Actuator line of action intersects joint hinge axis
.75	1.00	1.25	Actuator line of action intersects joint hinge axis
1.00	.50	1.00	Actuator intersects truss member E-E
1.00	.75	1.00	Actuator intersects truss member E-E
1.00	1.00	1.00	Actuator intersects truss member E-E
1.00	1.00	1.25	Actuator line of action intersects joint hinge axis
1.25	.50	1.00	Actuator inside transition truss structure
1.25	.75	1.00	Actuator inside transition truss structure
1.25	1.00	1.00	Actuator line of action intersects joint hinge axis

Table III. Articulated-Truss Joint Point Designs

	Joint A	Joint B	Joint C
Positive articulation limit, deg	180	180	130
Actuator length ratio at positive articulation limit	1.75	(a)	1.45
Normalized tip displacements:			
X-axis rotation	1.39	1.00	1.07
Y-axis lateral deflection	1.04	1.01	.96
Z-axis lateral deflection	1.20	1.07	1.01

[a]Actuator length ratio is not defined for joint concept B.

Table IV. Articulated-Truss Hardware Mass Properties

Measured masses:	
Battens/longerons, kg	0.63
Diagonals, kg	0.75
Reference truss node, kg	0.39
Actuators, kg	11.80
Joint hinge axis node A, kg	1.06
Estimated masses:	
Hinged nodes B, C, and F, kg	0.45
Trunnion node D, kg	2.27

Table V. Maximum Allowable Tip Velocities for Point Designs A, B, and C Subjected to an Emergency Stop Scenario

Point design		X-direction	Y-direction	Z-direction
A	Maximum tip velocity, m/s	0.65	0.46	0.12
	Articulation angle, deg	120	55	95
B	Maximum tip velocity, m/s	0.91	0.52	0.32
	Articulation angle, deg	75	10	95
C	Maximum tip velocity, m/s	0.13	0.32	0.16
	Articulation angle, deg	115	65	90

Table I. Truss Hardware Stiffness Properties

Truss member lengths (between node centers):	
Battens/longerons, m	1
Diagonals, m	1.414
Measured erectable joint properties:	
Length (node center to strut tube end), m	0.13
Axial stiffness, MN	8.45
Average bending stiffness, N-m^2	403.21
Estimated strut tube properties:	
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Diagonal length (between strut tube ends), m	1.15
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1.00	1.00	1.00	Actuator intersects truss member E-E
1.00	1.00	1.25	Actuator line of action intersects joint hinge axis
1.25	.50	1.00	Actuator inside transition truss structure
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	Articulation angle, deg	115	65	90

L-89-14712

Figure 1. Space crane and in-space construction facility.
(From *VOYAGE THROUGH THE UNIVERSE: Spacefarers*, art by Joe Bergeron, c.1989 Time-Life Books Inc.)

(a) Two-bay repeating unit.

(b) Truss beam.

Figure 2. Four-longeron reference truss geometry.

(a) Schematic.

(b) Perspective sketch.

Figure 3. Joint concept A.

(a) Schematic.

(b) Perspective sketch.

Figure 4. Joint concept B.

(a) Schematic.

(b) Perspective sketch.

Figure 5. Joint concept C.

Figure 6. Fourteen-bay reference truss analysis model. Static loads applied at 15th batten plane.

Figure 7. Representative articulated-truss joint finite element model (joint concept C shown).

Figure 8. Actuator length ratio for joint concept A (180° positive articulation limit).

Figure 9. Normalized X-axis tip rotation for joint concept A.

Figure 10. Normalized Y-axis tip deflection for joint concept A.

Figure 11. Normalized Z-axis tip deflection for joint concept A.

Figure 12. Normalized X-axis tip rotation for joint concept B.

Figure 13. Normalized Y-axis tip deflection for joint concept B.

Figure 14. Normalized Z-axis tip deflection for joint concept B.

Figure 15. Positive articulation limits for joint concept C.

Figure 16. Actuator length ratios at positive articulation limit for joint concept C.

Figure 17. Normalized X-axis tip rotation for joint concept C.

Figure 18. Normalized Y-axis tip deflection for joint concept C.

Figure 19. Normalized Z-axis tip deflection for joint concept C.

(a) Point design A.

(b) Point design B.

(c) Point design C.

Figure 20. Point designs selected from articulated-truss joint concepts A, B, and C.

Figure 21. Natural frequencies for point design A (no tip mass).

Figure 22. Natural frequencies for point design B (no tip mass).

Figure 23. Natural frequencies for point design C (no tip mass).

Figure 24. Natural frequencies for point design A with tip mass.

Figure 25. Natural frequencies for point design B with tip mass.

Figure 26. Natural frequencies for point design C with tip mass.

Figure 27. Maximum tip velocity for emergency stop scenario (point design A with tip mass).

Figure 28. Maximum tip velocity for emergency stop scenario (point design B with tip mass).

Figure 29. Maximum tip velocity for emergency stop scenario (point design C with tip mass).

Figure 30. Mode shape associated with lowest tip velocity for point design A. Articulation angle: 95°; mode shape: beam root torsion.

Figure 31. Mode shape associated with lowest tip velocity for point design B. Articulation angle: 95°; mode shape: beam root torsion.

Figure 32. Mode shape associated with lowest tip velocity for point design C. Articulation angle: 115°; mode shape: joint bending.

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(b) Perspective sketch.

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Figure 10. Normalized Y-axis tip deflection for joint concept A.

Figure 11. Normalized Z-axis tip deflection for joint concept A.

Figure 12. Normalized X-axis tip rotation for joint concept B.

Figure 13. Normalized Y-axis tip deflection for joint concept B.

Figure 14. Normalized Z-axis tip deflection for joint concept B.

Figure 15. Positive articulation limits for joint concept C.

Figure 16. Actuator length ratios at positive articulation limit for joint concept C.

Figure 17. Normalized X-axis tip rotation for joint concept C.

Figure 18. Normalized Y-axis tip deflection for joint concept C.

Figure 19. Normalized Z-axis tip deflection for joint concept C.

(a) Point design A.

(b) Point design B.

(c) Point design C.